PROJECT AUTHORIZATION NO. HWY- 2005 -13
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MASTER AGREEMENT FOR RESEARCH AND TRAINING SERVICES BETWEEN THE NORTH CAROLINA DEPARTMENT OF TRANSPORTATION AND NORTH CAROLINA STATE UNIVERSITY ON BEHALF OF THE INSTITUTE FOR TRANSPORTATION RESEARCH AND EDUCATION
(Contract No. 98-1783)

Project Title: Development of APA Design Criteria for Surface Mixtures

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Key Personnel: Dr. N. Paul Khosla

Project Monitor: _Mr.Mustan Kadibhai, PE

Additional Terms and Conditions: Research Project Guidelines as posted on ITRE's website at *http://itre.ncsu.edu/research/ongoingguidelines.htm.*

IN WITNESS WHEREOF, the parties hereto have executed this Project Authorization as of

_________________________, 2004.

NORTH CAROLINA STATE UNIVERSITY

BY:________________________________
Principal Investigator

BY:________________________________
N. C. State University

BY:________________________________
Director of ITRE

NORTH CAROLINA DEPARTMENT OF TRANSPORTATION

BY:____________________________

		HWY 2005-13
		NCDOT
		Research Proposal
Amount of Funds Requested:		$ 186,159
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Project Title:		**Development of APA Design Criteria for Surface Mixtures**
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DEVELOPMENT OF APA DESIGN CRITERIA FOR SURFACE MIXTURES

HWY 2005-13

by

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Executive Summary

Several test methods are in practice to assess the rutting potential of a mixture. The commonly used procedures are Diametral tests, Uniaxial test, Triaxial tests, Shear tests, Empirical tests, and Simulative tests. Of all these test methods, simulative test methods are relatively easier to use and ready for immediate adoption. The APA test is the most widely used simulative test. It is imperative that the rut depth criteria for the APA test should be developed for its employment. In a recent study conducted at NCSU, it was concluded that the APA could clearly detect poorly performing mixtures. With the limited availability of data, a reasonable correlation was observed between the APA tests and Repeated Shear at Constant Height (RSCH) tests. In view of this, a comprehensive research study should be conducted on all the surface mixtures used in North Carolina to develop the rut depth criteria. The rut depths measured from the APA tests would be compared with the corresponding shear strains of the RSCH test. Statistical analysis would be performed on the test results as measured by the APA and the RSCH tests. In addition, the APA test would be fine-tuned by addressing many issues related to air voids, test temperatures, gradations and aggregate sources. The correlations estimated using the data obtained from the APA and Shear tests would be used to develop rut depth criteria for the APA test. The developed rut depth criteria for the APA test could be adopted for immediate use in practice.

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Introduction

The most common type of distress on asphaltic pavements is rutting. Rutting is defined as the accumulation of small amounts of unrecoverable strain resulting from applied wheel loads to HMA pavement. This deformation is caused by excessive traffic consolidation or plastic deformation due to insufficient mixture stability. Rutting is likely to be a sudden failure that would occur in the early stages of a pavement's life. Rutting not only decreases the useful life of a pavement but also creates a safety hazard for the traveling public. Thus, it is important to estimate the rutting potential of a mixture before construction.

Several test methods are in practice to assess the rutting potential of a mixture. The commonly used procedures are Diametral tests, Uniaxial tests, Triaxial tests, Shear tests, Empirical tests, and Simulative tests. Of all these test methods, simulative test methods are relatively easier to use and ready for immediate adoption. Simulative test methods are basically accelerated laboratory rutting prediction tests. These tests are needed for design as well as quality control/quality assurance purposes. There are several loaded wheel testers in the United States. These devices potentially could be used to identify HMA mixtures that may be prone to rutting. Loaded wheel testers (LWT) are becoming increasingly popular with transportation agencies as they seek to identify hot mix asphalt mixtures that may be prone to rutting.

Problem Statement

Of the different laboratory rut testers, the Asphalt Pavement Analyzer (APA) is the most widely used loaded wheel tester. The APA test is not a fundamental test for permanent deformation. It can be considered as a simulative test, which simulates the traffic loading and temperature effects on compacted asphalt mixtures. It is simple to perform and uses cylindrical specimens compacted using the SGC. Various studies have demonstrated the performance of the APA. It would be prudent to compare the APA test results with the results for fundamental tests obtained on a large variety of asphalt mixtures. This would facilitate development of rut depth criteria for APA corresponding to similar criteria for fundamental tests.

In a recent study conducted at NCSU, it was concluded that the APA could clearly detect poorly performing mixtures [1]. It was found that the APA was sensitive to different compaction methods and gradations. With the limited availability of data, a correlation was attempted between the estimated rut depths from the Repeated Shear at Constant Height test (RSTCH) and the rut depths from the APA test. The rut depths from RSCH tests were estimated from their measured values of shear strains. The criterion for RSCH test is to terminate the test either at 5% shear strain or at 5000 cycles of loading. Therefore, the test was stopped even before the end of 5000 cycles if the mixture reached 5% shear strain. This strain corresponds to the maximum allowable rut depth of 0.5-inch rut depth, as prescribed by the SHRP surrogate models. Inspite of the limitation of termination of the tests at 5% shear strain, a reasonable correlation with R^2 value of 0.78 was observed between the RSCH tests and APA tests, as shown in Figure 1. If the RSCH tests on the failed mixtures were conducted till 5000 loading cycles beyond the maximum allowable strain of 5 percent, the correlation would be stronger with improved R^2 value. Moreover, it was observed that the mixtures, which failed to satisfy the RSCH test criteria, had rut depths greater than 0.5 inch, as measured by the APA. The mixtures that passed the RSCH tests had rut depths less than 0.5 inch. **The above observations strengthen the fact that there exists a strong correlation between a simulative test like APA test and a fundamental test like RSCH test.**

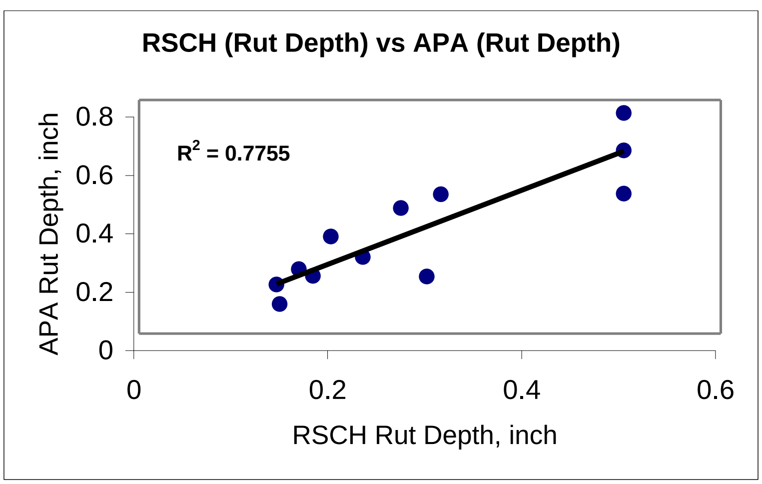

Figure 1. Correlation of RSCH Rut Depth and APA Final Rut Depth

In spite of a good correlation, there are plenty of other issues that need to be addressed. An earlier research conducted on the APA showed that this test was sensitive to aggregate sources and asphalt binder PG grade. The test results showed that the rut depths were significantly different for the same mixtures made with different aggregates such as limestone, granite and gravel. There are two different concepts in the specification of air voids for the simulative tests. First, some believe that specimen air void contents should be approximately 7 percent, since this air void content represents typical as-constructed density. Others believe that test specimens should be compacted to 4 percent air voids, as actual shear failure of mixes usually takes place below approximately 3 percent. As a convention, the APA tests are conducted at 7 percent air voids whereas the RSCH tests are conducted at 4% air voids. The effect of different air voids on the predictability of these test systems needs to be addressed.

The APA tests are conducted at two different test temperatures - high temperature of standard PG grade based upon climate, and 6^{o} C higher than high temperature of standard PG grade. The RSCH tests are conducted at the seven-day average high pavement temperature at 50-mm depth from pavement surface at 50% reliability. This temperature differs for each location. The application of different test temperatures would influence the rutting criteria for the APA. These limitations could be overcome if a reliable and dependable rut depth criteria for the APA test could be developed.

Research Objectives

The primary objectives of this research study will be to:

1. Conduct APA and Shear tests on all the surface course mixtures used by the NCDOT.
2. Develop correlations of Shear tests and APA test data.
3. Fine-tune the APA test by considering different air voids, test temperatures and aggregate sources and quantify the effect of these variables on the predictability of the APA.
4. Develop and recommend the APA test criteria for evaluation of rutting potential of the mixtures.

Literature Review

The Asphalt Pavement Analyzer (APA) is a modification of the Georgia Loaded Wheel Tester (GLWT) and was first manufactured in 1996 by Pavement Technology, Inc. The APA is a multifunctional loaded wheel tester used for evaluating permanent deformation (rutting), fatigue cracking, and moisture susceptibility of both hot and cold asphalt mixes. The APA can test gyratory, vibratory, Marshall specimens, field cores and roadway slabs in a temperature controlled chamber. A repeated load is applied to the test specimens in a dry or wet condition [2].

An earlier study conducted by Lai demonstrated the use of the GLWT. The rut depths of various mixtures measured using the GLWT were proportional to their Marshall's stability values [3]. A study conducted by the FHWA evaluated the ability of three LWT devices including the APA to predict or rank the field performance of WesTrack. Samples taken from 10 rehabilitated test sections at WesTrack were tested using the APA. The results were compared with WesTrack performance. The correlation (R^2=89.9%) was observed between the APA and WesTrack performance [4].

The Florida Department of Transportation conducted an investigation with the APA similar to the GLWT study described previously [5]. The authors observed that the APA ranked the mixtures according to their field performance ranking. They suggested that average values within the range of 7 to 8mm and of 8 to 9mm may be used as a performance limiting criteria at 8000 cycles for beam and gyratory samples, respectively.

Studies by Kandhal and Mallick observed that the APA is sensitive to aggregate gradation as the mixes with gravel and limestone aggregates generally had higher rutting than with granite [6]. The APA had a fair correlation (R^2=0.62) with the repeated shear constant height (RSCH) test conducted with the Superpave shear tester. Based on very limited data, the authors suggested that the APA rut depth after 8000 passes should be less than 4.5 mm to minimize rutting in the field.

A study at NCAT assessed the available LWTs regarding specific considerations, such as simplicity, test time, cost of equipment, availability of data to support use, published test method, available criteria, and so on. The study recommended that the APA can be adopted for use in mix design and QC/QA. It recommended a criterion of 8mm for APA rut test at the end of 8000 cycles [7].

Research Methodology and Tasks

Task 1 – Materials and Mix Designs

Currently, the NCDOT uses four surface course mixtures including two 9.5mm mixtures and two 12.5mm mixtures. The job mix formula of these mixtures will be obtained from the NCDOT. It is proposed to include all the surface course mixtures and three aggregate sources in this study. The aggregate sources will be selected in consultation with the NCDOT. The mix design criteria of these mixtures are given in Table 1.

Table 1. Mix Design Criteria of Surface Mixtures Approved by NCDOT

Mix Type	Design ESALs millions	Binder PG Grade	No. of Gyrations		
			Nini	Ndes	Nmax
S-12.5C	3-30	70-22	8	100	160
S-12.5D	>30	76-22	9	125	205
S-9.5B	0.3-3	64-22	7	75	115
S-9.5C	>30	70-22	8	100	160

Task 2 - Asphalt Pavement Analyzer (APA) Test

The rutting susceptibility of the mixtures is assessed by placing rectangular or cylindrical samples under repetitive loads of a wheel-tracking device, known as the Asphalt Pavement Analyzer (APA). The equipment is designed to evaluate not only the rutting potential of an asphalt mixture, but also its moisture susceptibility and fatigue cracking under service conditions. The APA is capable of testing both gyratory (cylindrical) specimens and beam specimens. The theory behind a loaded wheel tester is to apply an appropriate cyclical loading to asphalt concrete specimens to best simulate actual traffic. This is accomplished by air pressurized hoses laying across samples with a loaded wheel coming in contact with the hose and applying a predetermined load to the hose and thus the specimens. The wheel roles back and forth up to 8,000 times or cycles and the rut depth is then measured.

The APA test would be conducted on all the surface mixtures. The test would be conducted at two different air voids (4% and 7%) and the following four different test temperatures:

1. High temperature of standard PG grade based upon the climate (T1)
2. 6^{o} C higher than high temperature of standard PG grade (T2)
3. 6^{o} C lower than high temperature of standard PG grade (T3)
4. Seven-day average high pavement temperature at 50-mm depth from pavement surface at 50% reliability (T4).

The APA test is generally conducted at the first two temperatures, T1 and T2. The Repeated Shear test at constant height is performed at the seven-day average high pavement temperature. The APA test will be done at these three temperatures to see the influence of temperature on the correlation between the APA rut depths and RSCH rut depths.

Generally, the APA test is conducted on a pair of cylindrical specimens of a mixture. The data acquisition system of the APA measures the rut depths at four points of these paired specimens and plots the average value, which is used as the final rut depth of that mixture. The rut depths of each individual specimen would be measured. It is intended to increase the sample size from two to four for the purpose of a more robust statistical analysis.

As a practice, the rut depth is depth at the end of 8000 cycles. It is observed from the research study conducted at NCSU [1] that for most of the mixtures in the study the initial rutting rate was higher than the final rutting rate. After approximately 1,000 cycles, the rate of deformation gradually decreased, as observed in Figure 2. The rut depth at the end of 1000 cycles was observed and a ratio called as “*Initial Rut Ratio*” was calculated. This ratio is the initial rut depth over the final rut depth. Initial rut ratio gives an indication about the early rutting potential of a mixture.

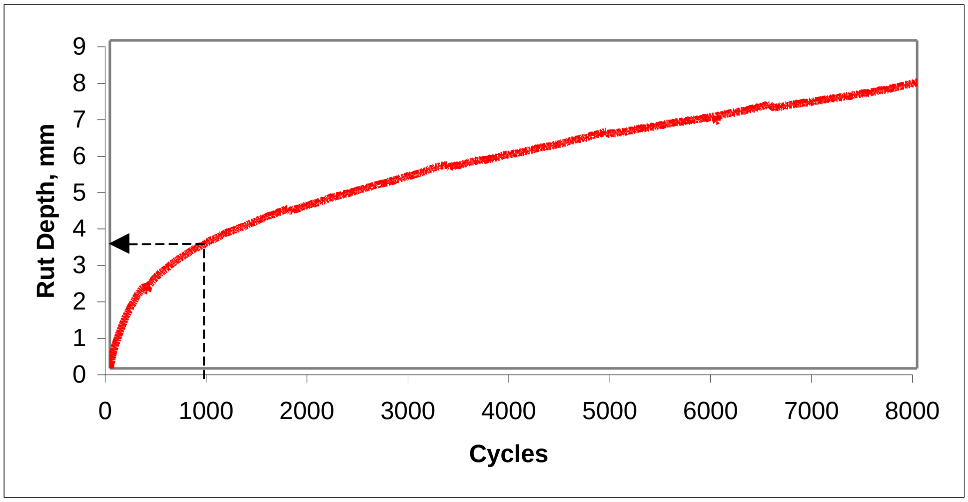

Figure 2. A Typical APA Test Curve: Rut Depth vs Loading Cycles

Task 3 – Shear Tests

The Simple Shear Tester (SST) was developed under SHRP as a way to measure the shear characteristics of HMA. Six tests can be performed with the SST for measuring the mix performance characteristics. The Simple Shear, Frequency Sweep at Constant Height, Uniaxial Strain, Volumetric Shear, Repeated Shear at Constant Stress Ratio, and Repeated Shear at Constant Height tests measure properties that may be useful in calculating the resistance to permanent deformation and fatigue cracking.

In this proposed study, Frequency Sweep Test at Constant Height and Repeated Shear Test at Constant Height will be used to analyze the performance of HMA mixtures. A full description of the test procedures can be found in AASHTO TP7 [8]. The rutting and fatigue analyses will then be conducted using the test results.

Task 3.1 Frequency Sweep at Constant Height (FSCH)

The Frequency Sweep Test at Constant Height is used to analyze the permanent deformation and fatigue cracking. A repeated shearing load is applied to the specimen to achieve a controlled shearing strain of 0.05 percent. The specimen is tested at each of the following loading frequencies: 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02 and 0.01 Hz. From the test results, dynamic shear modulus and phase angles for different frequencies are determined. The FSCH test will be performed on all the mixtures at both 4% and 7% air voids at 20^{o}C.

Task 3.2 Repeated Shear at Constant Height (RSCH)

This test is performed to estimate the rutting potential of a mixture. The accumulation of plastic shear strain in a mixture under repeated loading can give some indication about the mixture's resistance to permanent deformation. The Repeated Shear Test at Constant Height will be selected to evaluate the accumulated shear strain and permanent deformation characteristics of the mixture. This test is a stress-controlled test. A haversine shear pulse of 68 ± 5 kPa is applied for 0.1 second followed by a 0.6-second rest period for 5000 cycles. As explained earlier, it is proposed to perform this test till 5000 cycles even if the mixture reaches maximum allowable strain of 5 percent. This test will be performed at the seven-day average high pavement temperature at 50-mm depth from pavement surface at 50% reliability.

Task 3.3: Estimation of Rut Depths

The resulting shear strains from the RSCH tests are used to predict the pavement's performance under service for rutting. Rutting analysis are performed using surrogate models developed by SHRP 003-A project..

The rut depth is calculated using the following relationship:

$$\textit{Rut Depth (in.)} = 11 \times (g_p) \qquad (1)$$

where, γ_p= the maximum permanent shear strain in the RSCH test.

The conversion of the number of RSCH cycles to ESALS is done as follows:

$$\log(\textit{Cycles}) = -4.36 + 1.24 \log(\textit{ESALs}) \qquad (2)$$

Using the RSCH test results corresponding to 5000th load application (3 million ESALs), depths for mixtures will be estimated using the above equations.

Task 4 – Statistical Analysis of APA and Shear test results

An experimental plan developed for this proposed study is shown in Table 2. As mentioned earlier, the APA test would be performed for three gradations and two air voids at three temperatures and Shear tests would be performed for three gradations and two air voids at one temperature.

Statistical analysis would be performed on the test results as measured by the APA and the SST. The primary analysis tool selected for developing the rut test criteria for the APA test would be the simple correlation/regression analysis. The rut depths measured from the APA test would be compared with the corresponding shear strains of the RSCH test. The Asphalt Institute criteria would be used to interpret the RSCH maximum permanent shear strain. Table 3 shows the criteria for evaluating rut resistance using RSCH permanent shear strain. This table categorizes rut resistance of the mixtures based on their RSCH shear strain values.

The AI criteria for RSCH shear strain would be used for categorizing the mixtures according to their performance The rut depths estimated using the AI criteria would be used in the development of APA-RSCH correlation. A typical correlation of APA rut depths and RSCH rut depths is shown in Figure 3. Using the AI criteria, the RSCH rut depths would be estimated using the SHRP Rutting model. Figure 3 shows the categorization of mixtures based on the RSCH rut depth at 1%, 2% and 3% of their shear strain values. The RSCH rut depths, as calculated using the SHRP model, are 2.8mm, 5.6mm and 8.4mm at 1%, 2% and 3% shear strains, respectively. The corresponding APA rut depths at these shear strains would be estimated. The mixtures can then be categorized as excellent, good, fair or poor performing mixtures.

Table 2. Experimental Plan

Mixture	Aggregate Source	Air Voids	APA Test				Shear Test	
			T1	T2	T3	T4	FSCH 20^{o}C	RSCH T4
S-12.5C	A1	4%	4*	4	4	4	4	4
		7%	4	4	4	4	4	4
	A2	4%	4	4	4	4	4	4
		7%	4	4	4	4	4	4
	A3	4%	4	4	4	4	4	4
		7%	4	4	4	4	4	4
S-12.5D	A1	4%	4	4	4	4	4	4
		7%	4	4	4	4	4	4
	A2	4%	4	4	4	4	4	4
		7%	4	4	4	4	4	4
	A3	4%	4	4	4	4	4	4
		7%	4	4	4	4	4	4
S-9.5B	A1	4%	4	4	4	4	4	4
		7%	4	4	4	4	4	4
	A2	4%	4	4	4	4	4	4
		7%	4	4	4	4	4	4
	A3	4%	4	4	4	4	4	4
		7%	4	4	4	4	4	4
S-9.5C	A1	4%	4	4	4	4	4	4
		7%	4	4	4	4	4	4
	A2	4%	4	4	4	4	4	4
		7%	4	4	4	4	4	4
	A3	4%	4	4	4	4	4	4
		7%	4	4	4	4	4	4

A1, A2, A3 : Three Different Aggregate Sources
T1, T2, T3, T4: Four Different Test Temperatures
* Number of Replicates
Total Number of Specimens: 576

Table 3. AI Criteria for Evaluating Rut Resistance Using RSCH Permanent Shear Strain

Shear Strain, %	RSCH Rut Depth from SHRP Model, inch	Rut Resistance
< 1	< 0.11	Excellent
1 to < 2.0	0.11 – 0.22	Good
2 to < 3.0	0.22 – 0.33	Fair
> 3.0	0.33	Poor

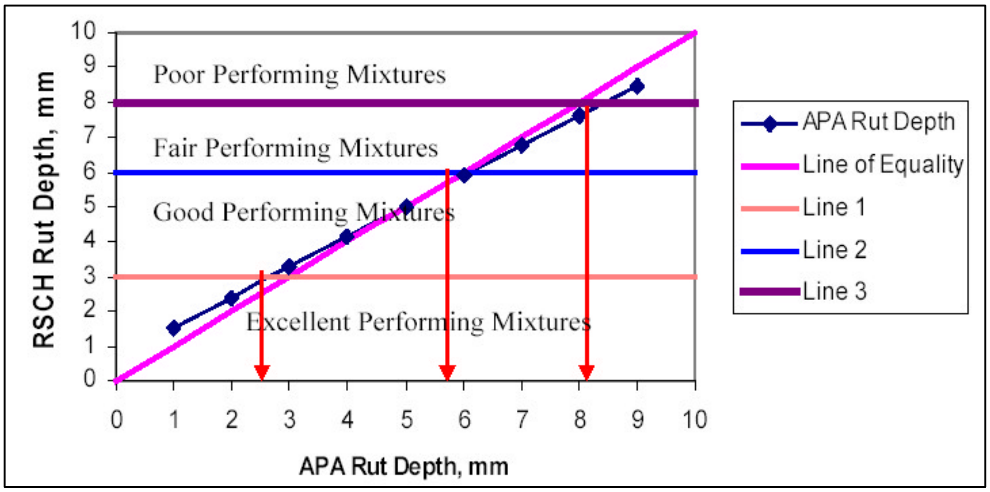

Figure 3. Expected Correlation

Anticipated Benefits and Outcomes

The proposed study will provide a simple and effective methodology and design criteria for using APA for Superpave surface mixtures. The rut depth criteria could be implemented for all the new surface mix designs and test contractor submitted specimens for compliance. The implementation would result in better overall pavement performance and possibly less rutting in HMA pavements in North Carolina.

Recommendations for Implementation and Technology Transfer

In this study, rut depth criteria for using APA would be developed for surface mixtures used by NCDOT. The results and recommendations of the study could be easily implemented into practice.

Resources to be supplied by NCDOT

As NCSU does not own an APA, the facilities in the Materials and Tests Unit of NCDOT will be used to perform the APA tests. The amount of raw materials required will be decided in consultation with NCDOT.

Equipment and Facilities

A state-of-the-art equipment related to the proposed research project is available in the construction materials research laboratories at NCSU.

Time Requirements

The duration of the proposed research project is 24 months. It is anticipated that the items of work will proceed according to the work schedule in Table 4. As the APA and the Shear Tester would be used by several researchers on different research projects, the availability of this equipment is not on continuous basis and has to be scheduled to accommodate other on-going research work.

Qualifications and Accomplishments of Researcher

Dr. Khosla has been on the faculty of Civil Engineering at NCSU for the last 23 years and currently holds a position of a full professor in the Department. He has been an active researcher and has been a Principal Investigator on projects with total funding in excess of $6.0 million. These research projects have been funded through NSF, FHWA, USDOT, NCHRP, and NCDOT. Dr. Khosla is very familiar with the design and performance of asphaltic mixtures and pavements and is eminently qualified to undertake the proposed research study.

List of Related Publications

[1] N. Paul Khosla and Suriyanarayanan Sadasivam, "*Evaluation of the Effects of Mixture Properties and Compaction Methods on the Predicted Performance of Superpave Mixtures*," FHWA/NC/2002-030, Final Report Submitted to NCDOT, 2002.

[2] Performance Related Testing With The Asphalt Pavement Analyzer, Technical Paper T-137 http://www.pavementtechnology.com/Tech%20Papers/tech_paper_t137.htm

[3] Lai, JS and Lee, TM., " Use of a Loaded-Wheel Testing Machine to Evaluate Rutting of Asphalt Mixes," Transportation Research Board, Transportation Research Record 1269, 1990, pp 116-124

[4] Williams, RC and Prowell, BD, "Comparison of Laboratory Wheel-Tracking Test Results with Westrack Performance," Transportation Research Record - Journal of the Transportation Research Board 1681, 1999 pp 121-128

[5] Choubane, B, Page, GC and Musselman, JA. Suitability of Asphalt Pavement Analyzer for Predicting Pavement Rutting ,Transportation Research Record 1723, 2000, pp 107-115

[6] Prithvi S. Kandhal and Rajib B. Mallick, "Evaluation of Asphalt Pavement Analyzer For HMA Mix Design," NCAT Report No. 99-4 http://www.eng.auburn.edu/center/ncat/reports/rep99-4.pdf

[7] Brown, E.R., Kandhal, P.S. and Jingna Zhang, "Performance Testing for Hot Mix Asphalt," NCAT Report No. 01-05, National Center for Asphalt Technology, Auburn, November 2001

[8] Monismith, C. L., "Asphalt Concrete: An Extraordinary Material for Engineering Applications," 13th Henry M. Shaw Lecture in Civil Engineering, Department of Civil Engineering, North Carolina State University, Raleigh, 1993.

TABLE 4 – PROPOSED WORK SCHEDULE